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IMPROVED OPERATION AND MODELING OF THE SSPX SPHEROMAK*

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The Sustained Spheromak Physics Experiment, SSPX, is a 1m diameter magnetized coaxial gun-driven spheromak experiment at the Lawrence Livermore National Laboratory designed to explore the physics of confinement and magnetic field generation [1]. Here we report significant advances in the operation of SSPX and in modeling spheromak physics with improved comparisons to experimental data.

The highest measured T_e and lowest core thermal diffusivity ($\chi_e \sim$ 10-20m^2/s) occurs when the edge magnetic fluctuation amplitude ($|\delta B/B|_{rms}$) is lowest. Improvements over previous results [2] were produced with higher formation bank current, longer discharges, and better matching of edge current and bias flux to minimize $|\delta B/B|_{rms}$. Optimal operation is obtained by flattening the profile of $\lambda=\mu_0 j/B$, consistent with reducing the drive for tearing and other MHD modes. This is achieved by operating the injector at currents such that $\lambda_g=\mu_0 I_g/\psi_g$ approximately equals the eigenvalue of $\nabla\times\mathbf{B}=\lambda\mathbf{B}$ for the flux conserver. (ψ_{gun} = applied poloidal magnetic flux.) With the new optimizations, T_e increased from 120 eV to >200 eV with the peak value close to the magnetic axis determined by fitting MHD equilibria to magnetic probe data. The peaked temperature profiles are limited in minor radius by poor-confinement regions suggesting the existence of good magnetic surfaces in a central region. To test the quality of the magnetic surfaces, a symmetry-breaking coil was installed external to the vacuum vessel, which provided a static, non-axisymmetric perturbing magnetic field. Depending on the polarity of the current in the coil, the central temperature was reduced or increased. To analyze this experiment, Monte-Carlo calculations of heat transport have been undertaken. As the magnetic perturbation is turned up, the modeling indicates that the energy confinement time exhibits sharp transitions.

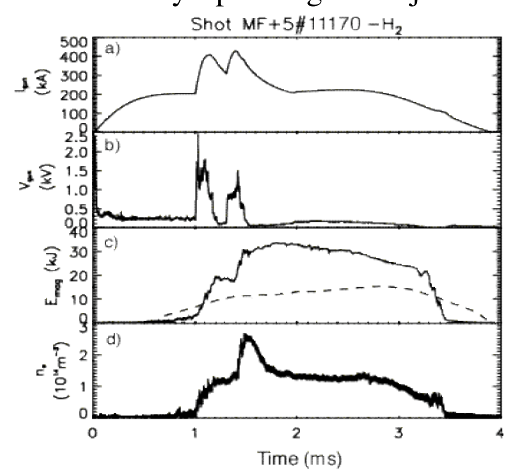

Fig 2.a) gun current; b) gun voltage; c) magnetic energy of the spheromak for double pulse (solid) and for steadily building discharges (dashed [5]); d) chord-averaged density from interferometry.

New experiments show for the first time that the field energy of the spheromak can be increased in a step-wise manner using repetitive current pulses. On SSPX the external circuit impedance is larger than the plasma impedance, so inductive and resistive processes that occur in the plasma determine the injector voltage. One such process

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occurs when the injected current kinks along the geometric axis: this has been found to saturate at a magnetic field strength consistent with dissipation, which when pulsed has led to an increase of the spheromak magnetic field energy. Figure 1 shows the results from the experiment for which the current source was pulsed twice, clearly giving a stepwise increase of the stored energy (in this case from 18kJ to 32kJ). By this means, the highest magnetic fields have been produced in SSPX (0.7T at the geometric axis), and an important scaling of magnetic field with current has been exceeded.

Energy confinement in spheromak plasmas is being investigated with the NIMROD code. Previous work [3] considered the low-pressure limit of MHD and shows that plasma current driven by electrodes pinches and forms a configuration that is unstable to an n=1 toroidal mode, whose saturation amplifies the poloidal flux and forms the spheromak. With temperature-dependent collisional thermal transport coefficients and electrical resistivity, the cold edge plasma tends to impede parallel thermal conduction to the wall in sustained conditions. When the drive is removed, the cold edge plasma assists magnetic reconnection and closed magnetic flux surfaces form rapidly. Core temperatures then increase to approximately 100 eV as magnetic energy is converted to thermal energy by Ohmic heating. The simulated temperature evolution and magnetic field parameters compare well with laboratory measurements (see Fig. 2).

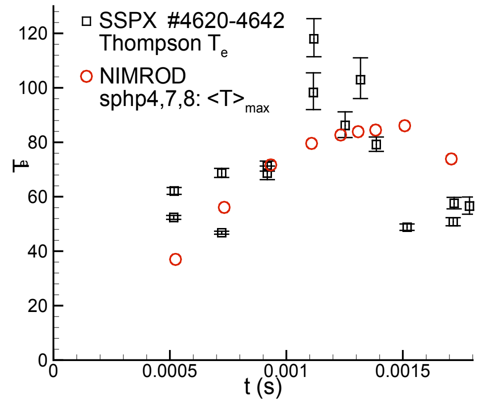

Fig 2. Peak electron temperature from the SSPX experiment and from NIMROD simulations during a transition from driven to partially sustained conditions.

We are also using NIMROD and analytic theory to study multi-pulse operation and investigate the role of ideal helical central-column instabilities in a “pillbox” configuration (uniform axial field bounded by conducting end plates) and other geometries. Most recently, we have examined the stabilizing influence provided by a cylindrical conducting rod inserted along the geometric axis.

We have made other advances in understanding spheromak field generation and confinement. New measurements in the injector region show for the first time that the magnetic flux exits the gun non-uniformly. The axial current density flowing in the gap is similarly toroidally asymmetric, resulting in strong variation of the local □ in the gap. From these data we conclude that a large fraction of the gun current crosses field lines inside the flux conserver. In addition, we recently embarked upon an extended campaign aimed at exploring the isotope effects on SSPX. We have compared several hundred (~500) deuterium discharges with a similar number of discharges in hydrogen. The D_2 fueled discharges show similar results to those with H_2 fueling, including comparable density and peak electron temperatures of ~200eV. Furthermore, little difference in spheromak formation dynamics or characteristic MHD behavior is observed.

[1] E. B. Hooper *et al.*, Nuclear fusion **39**, 863 (1999).
[2] H. S. McLean *et al.*, Phys. Rev. Lett. **88**, 125004 (2002).
[3] C.R. Sovinec, J. M. Finn, and D. del-Castillo-Negrete, Phys. Plasmas **8**, 475 (2001).